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The Mechanical Properties of Masonry Walls - Analysis of the Test Results

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Abstract

This paper presents an analysis of the test results of mechanical properties of masonry walls. As part of the planned research the main goal is to determine the compressive strength, elasticity modulus, shear modulus, and the characteristic steadiness on the tensile of the masonry walls. Experimentally determined values for the modulus of elasticity of the tested walls are higher than those provided in regulations PIOVS'91, EN 1996-1-1: 2005; ACI 530. Values of characteristic compressive strength obtained analytically and based on equations that are given in national and international standards are larger than the values of the characteristic compressive strengths of the walls that we have examined. This study is relevant for Montenegro, which is a seismically dangerous zone.

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Keywords: masonry walls, clay block, concrete block, mortar, testing, compressive strength.

1. Introduction

The considerable destruction in the old town centers of coastal towns, as well as in rural areas caused by the earthquake which struck Montenegro in 1979 was recorded. The earthquake had a magnitude of 7.0 on the Richter scale and caused catastrophic devastation with the intensity of IX degrees within a radius of over 100 km. The

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largest number of fatalities from the earthquake were within buildings built of clay and stone.

Quality control of materials used to build the modern masonry buildings, masonry elements and mortar, on the territory of Montenegro, is almost never performed. Also supervision during construction is often lacking. Clay block, which has very different mechanical properties, is commonly used as an element for building masonry walls. In the period 1990-2000, because of the wars in the region and the imposed economic sanctions, a large number of individual objects is built of concrete block or clay block, which do not meet the minimum required compressive strength. According to the still applicable Yugoslavian regulations for masonry, a prescribed minimum compressive strength of masonry is 10 MPa.

Data on the mechanical properties of masonry walls from the materials used in Montenegro are scarce. Data on the characteristics of the stone walls were published, because the in-situ testing was performed during the repair of buildings of stone, after the earthquake of 1979. There is no published data from the Montenegro researchers on determining the mechanical characteristics of the masonry walls of clay block or concrete block. Today, the largest population of Montenegro live in masonry buildings. In the case of strong earthquakes, it can be expected that the largest number of casualties and damages to be registered, will be from buildings with masonry structure.

2. The goal of the research

In the framework of a national research project entitled "Seismic risk reduction in buildings of stone and brick" is planned to launch base research in the field of masonry structures. The goal is to test the mechanical properties of the walls from elements of masonry which are used often in the Montenegro construction practice. In the first phase of testing we tested walls build with elements of masonry and assumed that their mechanical properties are below the prescribed limit. It was planned by the project to define the mechanical characteristics of masonry walls from hollow clay block, concrete block and clay block; to explore the rational methods of repairing and strengthening of masonry structures and to propose how this research can be incorporated into the Montenegro regulations.

As part of the planned research the main goal is to determine the compressive strength, elasticity modulus, shear modulus, and the characteristic steadiness on the tensile of the masonry walls (the value of principal tensile stress at the time of collapse). Limited availability of measuring equipment was a factor in designing the experiment and the choice of methods of testing of masonry walls.

Mechanical characteristics of masonry walls depend on the mechanical characteristics of elements of masonry and mechanical characteristics of mortar, to a large extent. In order to define the influence of the mechanical characteristics of mortar on the compressive strength of masonry walls, and on the tensile in the direction of the principal tensile stress, it was decided to built more wall samples from the same kind elements of masonry, where the different samples used the different brands of mortars for a masonry, in order to analyze the influence of the quality of the binder on the mentioned mechanical characteristics of masonry walls.

In the period June-July 2014 testing of masonry walls on the pressure were conducted, on the basis of the measured deformations for the walls made of clay block and concrete block are defined: compressive strength, elastic modulus, Poisson's ratio and shear modulus.

Ahead of us is to determine the characteristic tensile strength of masonry walls. We will determine characteristic tensile strength of masonry walls after testing the samples by applying compressive force on the diagonal. Based on these measurements we will determine the values of the main tensile stresses in the masonry walls of clay block, concrete block and a hollow clay block in mortar of different brands.

Samples of linings, which potentially could be rationally used in recovery of the masonry walls, were tested for tension. The tested samples had as a matrix "Betonprotekt K2" or "Ytong ljepilo". Linings are reinforced with steel mesh or thin voice mesh, in one or two layers.

It was a plan to test the possibility of injecting the walls with the injection mixtures composed by our own recipes, so we would be able to determine the contribution of injection on the stiffness and the bearing of walls. Also, the goal was to experimentally confirm the coating contribution to the mechanical characteristics. The research will be accompanied by the software analysis of the behavior of the model object. The plan is to use the software "Perform 3D". In the model object, walls will have the same thickness and mechanical properties as well as the walls we tested in the laboratory. The realization of this very ambitious plan of the research very much depends on the technical and financial capabilities, which are currently very limited [1-12].

3. Testing the characteristics of materials

Material testing consists of testing ingredients of mortar, mechanical characteristics of mortar and masonry elements. In order to determine the composition of the mortar with a predetermined strength, it is necessary to determine the basic characteristics of the aggregates, cement and lime.

3.1. Testing aggregates

The testing of aggreagates consisted of determining: granulometric composition, fineness modulus (M) and the density of the saturated surface of dry grains (γ_{zz}).

The granulometric composition of aggregates was determined according to the applicable standards MEST EN 933-2: 2009 (determining the geometric properties of aggregates) and MEST EN 933-1: 2012 (determination of granulometric composition of aggregates - the luster method). Because of the presence of grains larger than 2mm in masonry mortar its granulometric composition is adjusted according to the old standards for small aggregate JUS B.B2. 010, as equivalent European norms prescribing boundaries that small aggregate must meet for use in mortar for plastering weren't found (norm labeled MEST EN).

Fineness modulus of the test aggregate is M = 3.53, which meets the application for mortar for the masonry according to literature (M = 2.3-3.6).

Density of the aggregate was tested by current standards MEST EN 1097-6 : 2009.

3.2. Testing of cement and lime

This study determined the specific density of binders: cement and lime. Tests were conducted in accordance with JUS B. C8. 023, because the equivalent European Standards were not available. The obtained values of the specific density of the cement and lime, respectively, are: γ_{sc}= 2682 kg/m^3 and γ_{sk}= 2430 kg/m^3.

3.3. Testing mortar for masonry

The testing of mortars was conducted according to the following standards: MEST EN 1015-2: 2009 (sampling and preparation of samples for testing) and MEST EN 1015-11: 2009 (determination of compressive strength and bending). The study was conducted on 3 samples for every type of mix. The test results are given in table 1.

Table 1: Compressive strength of mortar

Expanding mortar:	PM1	PM2	PM3	PM4
Ratio Vc : Vk : Vp	1 : 0,75 : 5	1 : 0,5 : 6	1 : 0,25 : 4,25	1 : 0,2 : 3
Mean value of compressive strength, [MPa]	11,60	8,20	14,40	23,90
Class of mortar:	M10-1	M5	M10-2	M20

3.4. Testing of masonry elements

According to previous experimental studies, the most significant contributions to the mechanical properties of the masonry wall is given by mechanical properties of masonry elements. In order to assess the contribution of strength of masonry elements to the strength of the wall, it was decided as a part of the planned research, testing of mechanical characteristics was performed on samples of walls built from the different masonry elements, but with the same class of mortar. Samples of walls of the following types of masonry elements were built: hollow clay block "trokanalka" 25x12x6.5, clay block 25x19x19 and concrete block 38x19x19. The testing of the compressive strength of masonry elements was carried out in accordance with MEST 772-1: 2011, and the results are given in table 2.

Table 2: Results of testing compressive strength of masonry elements

	Hollow clay block	Clay block	Concrete Block
Sample:			
Dimensions of the sample, [mm]:	250x120x65	250x190x190	380x190x190
Mean value of compressive strength, [MPa]:	6,11	6,51	3,26
Brand of the masonry element:	MO 5	MO 5	MO 2

4. Examined walls

For calculation and testing we selected a combination of clay / block with multiple types of mortar. Hollow clay block is combined with mortar classes M5 and M10-2 (labeling the walls PM2 and PM3), while the walls of clay block and concrete block are combined with mortar classes M10-1, M10-2 and M20 (labeling the walls made of clay block : IM1, IM3 and IM4, and the walls of concrete block: BM1, BM3 and BM4).

4.1. Testing of compressive strength and elasticity modulus of masonry walls

The testing of compressive strength and elasticity modulus have been performed by the conditions defined in the standard EN 1052-1: 2011 - Test methods for masonry - Part 1: Determination of compressive strength.

4.2. Furnishing of samples

Samples were adequately equipped for determining the compressive strength, elasticity modulus and Poisson's ratio, in accordance with the technical capabilities and equipment owned by the laboratories of University of Civil Engineering in Podgorica. Devices that automatically measure movement - transducers (LVDT), were installed to measure the vertical dilatations. Two devices were placed on every face of the wall (4 in total). The measurement base of these devices is the middle third of the height of the sample. The principle of the setup is shown in Figure 1 a).

In Figures 1 b) and Figure 2 (a,b) the materialization of furnishing of samples is shown.

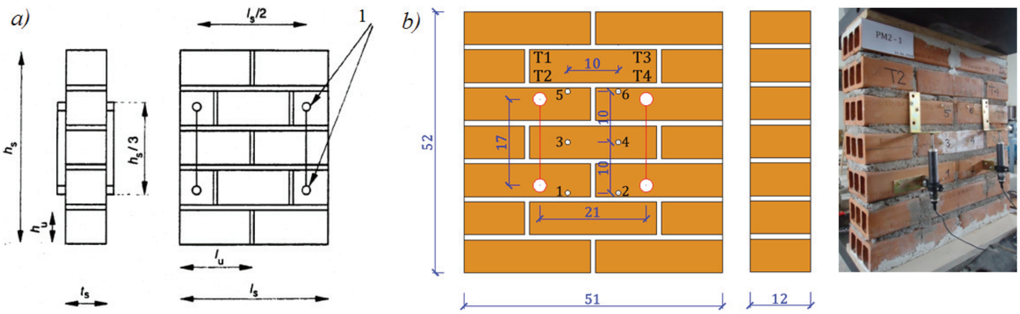

Fig. 1. a) Setting of the LVDT device; b) Hollow clay block walls

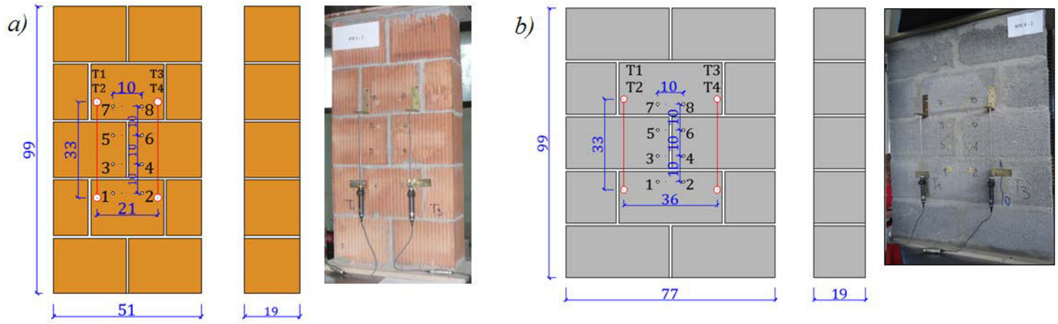

Fig. 2. a) Clay block walls; b) Concrete block walls

4.3. Course of the experiment

Prior to the experiment, in accordance with the standard EN 1996-1-1: 2005, the expected fracture forces have been calculated, in order to determine the steps ie. rate of loading. In accordance with the aforementioned standard, flow of the experiment is planned so that fracture of the masonry wall occurs after 15-30 minutes from applying the load. Fracture force of the first sample, for each group of three samples, was the guideline for determining the flow of the experiment for the other two samples.

The load was applied in steps, in at least three steps, until it reached 50% of the maximum expected fracture force. At each step, the force is kept as constant for 2min± 1min to measure the deformation in the LVDT and in the measuring points. After 50% of the force was applied on the sample, the rest was applied constantly (0.15 N / mm 2 per min - up to 1.25 N / mm 2 per minute, depending on the strength of samples) until the fracture.

When applying the load the values of the force when cracks appeared were observed (they are marked on the sample), the maximum potential force was measured (1 kN accuracy), and the length of time for the experiment.

5. Results of the testing walls under pressure

5.1. Determination of compressive strength

Method of processing data obtained by the experiment is defined by the standard. The terms of defining the compressive strength and elasticity modulus,as well as the determination of the characteristic values of compressive strength, are indicated.

The compressive strength of the individual samples, f_i, is defined as the ratio of the fracture force (maximum force $F_{i,max}$) and leaning area of the sample (A_i). f is the mean value of the compressive strength of the three tested samples. Characteristic values of compressive strength are given in Tables 3 and 4.

Table 3. Compressive strength of clay block walls - IM1, IM3 and IM4

Area (50,7x19) [cm]		Fracture force	fi	f	fk = f/1,2	fi,min	fk
		[kN]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]
IM1-	1	210,00	2,18				
IM1-	2	255,00	2,65	2,84	2,36	2,18	2,18
IM1-	3	355,00	3,69				
IM3-	1	285,00	2,96				
IM3-	2	340,00	3,53	3,10	2,58	2,80	2,58
IM3-	3	270,00	2,80				

IM4-	1	280,00	2,91				
IM4-	2	255,00	2,65	2,89	2,41	2,65	2,4
IM4-	3	300,00	3,11				

Table 4: Compressive strength of concrete block walls - BM1, BM2 and BM3

Area (77,1x19) [cm]		Fracture force	f_i	f	$f_k = f/1,2$	$f_k = f_{i,min}$	f_k
		[kN]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]
BM1-	1	300,00	2,05				
BM1-	2	350,00	2,39	2,16	1,80	2,05	1,80
BM1-	3	300,00	2,05				
BM3-	1	350,00	2,39				
BM3-	2	320,00	2,18	2,43	2,03	2,18	2,03
BM3-	3	400,00	2,73				
BM4-	1	400,00	2,73				
BM4-	2	380,00	2,59	2,90	2,42	2,59	2,42
BM4-	3	495,00	3,38				

5.2. The modulus of elasticity

Calculation of elasticity modulus E_i of each sample, is determined as the ratio of stress to a third of the maximum force (fracture force) and average value of dilatation for all four measurement devices (LVDT) at the force which is equal to one third of the maximum force, or through expression (1):

$$E_i = \frac{F_{i,max}}{3 \cdot \varepsilon_i \cdot A_i} \tag{1}$$

Where:
$F_{i,\,max}$ - fracture force;
ε_i - the mean dilatation measured on all four LVDT's, at the force equal to one third of the fracture force;
A_i - leaning area of the wall.

The modulus of elasticity is obtained as the mean modulus value of all samples in the group. Calculated modulus of elasticity are shown in Tables 5 and 6.

Table 5: Modulus of elasticity of clay block walls - (three classes of mortar)

Area (50,7x19) [cm]		Ei	E
		[GPa]	[GPa]
IM1-	1	2,79	
IM1-	2	2,52	2,88
IM1-	3	3,32	
IM3-	1	3,30	3,07

IM3-	2	3,27	
IM3-	3	2,65	
IM4-	1	3,03	
IM4-	2	3,18	3,19
IM4-	3	3,35	

Table 6: Modulus of elasticity of concrete block walls - (three classes of mortar)

Area (77,1x19) [cm]		Ei	E
		[GPa]	[GPa]
BM1-	1	8,53	
BM1-	2	4,58	6,44
BM1-	3	6,21	
BM3-	1	2,63	
BM3-	2	4,55	4,22
BM3-	3	5,48	
BM4-	1	3,75	
BM4-	2	8,91	6,60
BM4-	3	7,13	

5.3. An analytical approach to determining the characteristic of compressive strength and modulus of elasticity

In order to examine regulations defining of characteristic strength of masonry walls under pressure and modulus of elasticity, applicable Yugoslavian standard PIOVS'91, European standard EN 1996-1-1: 2005 and American standards ASTM E447 and ASTM C 270 were analyzed. Table 7 shows the values of compressive strength, modulus of elasticity and shear, obtained by applying the above standards.

Table 7. Values obtained by empirical expressions of the three standards

Label of the sample	Characteristic compressive strength of masonry wall f_k, [MPa]			Modulus of elasticity [GPa]			Shear modulus [GPa]		
	EC6	ACI	YU	EC6	ACI	YU	EC6	ACI	YU
IM1	2,97	4,06	3,72	2,97	2,84	3,72	1,19	1,14	0,60
IM3	3,17	4,39	3,92	3,17	3,07	3,92	1,27	1,23	0,63
IM4	3,69	4,71	4,45	3,69	3,30	4,45	1,48	1,32	0,71
BM1	2,09	3,41	2,37	2,09	2,39	2,37	0,84	0,96	0,38
BM3	2,23	3,57	2,50	2,23	2,50	2,50	0,89	1,00	0,40
BM4	2,60	3,74	2,84	2,60	2,62	2,84	1,04	1,05	0,45

Characteristic compressive strength of masonry walls as defined under the U.S. regulations are much higher than the characteristic compressive strength defined in accordance with the European and the applicable regulations, where these values are approximately the same. This may be a consequence of differences in the material properties of the masonry used in the United States, because the formula we used was adjusted to their standards. Analysis of all three standards leads to the conclusion that the equation pointed to the significant impact of compressive strength to elements of masonry on the compressive strength of the masonry wall. The modulus of elasticity by European and Yugoslavian regulations is determined in the same manner and the value is 1000^*f_k. American regulations have a distinction between the masonry element materials, so for clay elements elastic modulus is lower, amount of 700 f_k, while for concrete elements 900 f_k.

Shear modulus by American and European standards is defined as 40% E, but Yugoslavian regulation defines a substantially lower shear modulus (16% E). When calculating permanent effects, the recommendation is to adopt shear modulus as 0.40, while for the calculation of the seismic effect, the recommendation is to adopt as 0.16.

6. Comparison of the results

6.1. Characteristic compressive strength

Compressive strength depends on many factors, primarily of the compressive strength of masonry elements and compressive strength of mortar, of the thickness of a mortar's couplings and of the fulfillment of mortar's couplings (vertical and horizontal), as well as of the dimensions of masonry elements. An important role in the experimental determination of the compressive strength of the wall, is the aspect ratio of the sample wall thickness and height, the compressive strength of the masonry wall is lower as the ratio is larger. Quality of masonry has an impact on the value of the measured compressive strengths (if the wall is not completely vertical when receiving a force, we going to have the bending moment, which reduces the compressive strength of the wall).

Comparative review of the characteristic compressive strength calculated analytically and experimentally obtained is given in Table 8.

Table 8. Characteristic compressive strengths - analytical and experimental

Label of the sample	Characteristic compressive strength of wall f_k, [MPa]				
	EC6	ACI	YU	Σfi/3	$f_{k\ eksp.}$
IM1	2,97	4,06	3,72	2,84	2,18
IM3	3,17	4,39	3,92	3,10	2,58
IM4	3,69	4,71	4,45	2,89	2,41
BM1	2,09	3,41	2,37	2,16	1,80
BM3	2,23	3,57	2,50	2,43	2,03
BM4	2,60	3,74	2,84	2,90	2,42

6.2. The modulus of elasticity

Comparative review of elasticity modulus calculated analytically and obtained experimentally is given in Table 9.

Table 9. Modulus of elasticity – analytically and experimentally

Label of the sample	Modulus of elasticity E, [GPa]			
	EC6	ACI	YU	$E_{eksp.}$
IM1	2,97	2,84	3,72	2,88

IM3	3,17	3,07	3,92	3,07
IM4	3,69	3,30	4,45	3,19
BM1	2,09	2,39	2,37	6,44
BM3	2,23	2,50	2,50	4,22
BM4	2,60	2,62	2,84	6,60

The modulus of elasticity obtained experimentally for samples of clay block walls (code IM) is about $1300xf_k$, while for the samples of concrete block walls (marked BM) is about $2800xf_k$.

7. Conclusions

Comparing the obtained experimental results concludes that for the clay block walls with higher compressive strength of mortar does not necessarily mean greater strength of the wall.

Mortar in the couplings affects not only the compressive strength of the wall but the overall mechanism of fracture of the wall as well. The use of the mortar with higher compressive strength in the walls with the elements of small compressive strength decreases the load of the masonry wall, as it becomes more brittle. Based on the so far analyzed results of the experiment we observed that the increased amount of lime in the mortar's recipe, improves the ductility of the wall. This paragraph should be confirmed by additional analyzes.

Significant impact on the behavior of the wall and the fracture mechanism in the experiment, has the quality of building the samples walls. Fulfillment of the block's hollows with mortar affect the results. The recommendation is to put the mortar along the horizontal coupling, not just strips along the face of the wall, in order to more evenly disperse the strain. The recommendation for some further researches and experimental studies is a combination of masonry's elements and mortar of lower classes, in order to develop better behavior and better model of fracture of the masonry wall.

Values of characteristic compressive strength obtained analytically and based on equations that are given in our current regulations, European and American regulations are larger than the values of the characteristic compressive strengths of the walls that we have examined. Experimentally determined values for the modulus of elasticity of the tested walls are higher than those provided in these regulations.

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